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Correlation between reynolds number and limit flux during skim milk microfiltration

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The major limiting step in microfiltration is fouling being its immediate consequence the existence of a limit flux, i.e. a maximum flux can be obtained for each process condition (Cheryan, 1998). As a maximum, the limit flux determination is very important for any microfiltration processes and if this parameter can be related to a dimenssionless number, such as Reynold's number, it can be useful for microfiltration behavior prediction. For example, in chemical engineering the Reynold's number ($Re=\rho \cdot d_h \cdot v/\mu$) is usually used for friction factor estimation in drop pressure determination.

The aim of this work was to find the relationship between the limit flux (J_L) and the Reynolds number (Re) during skim milk microfiltration. A 25 cm length module and 0.14 micrometers ceramic membranes were used and two hydraulic diameters (d_h) of 3.6 and 6 mm were tested. The cross-flow velocities were 1.13, 2.90 and 4.29 m/s for the 3.6 mm (d_h) and for the 1.22, 3.13 and 4.64 m/s for the 6 mm (d_h). Moreover, three temperatures (40, 50 y 60 ºC) and four total protein concentrations (1.5, 3.0, 4.5 and 9.0 % w/w) were tested. Skim milk powder was used for preparing all milks with different total protein concentrations, representing different concentration factors during microfiltration in a range of 0.5 to 3.0. All experiences were carried out under total recirculation permeate mode.

The experimental limit flux value was determined as the maximum flux which can be obtained for each process condition. Additionally, same value was determined plotting (ΔP_T, J) points and fitting them to the empiric equation $J=a \cdot \exp(-b \cdot \Delta P_T)$. Because the empiric equation has an asymptotic behaviour toward J_L when ΔP_T increases, hence it was assumed that the "a" value is equal to the limit flux (J_L). No significant differences were found between the experimentally obtained value and the determined by the empirical equation. On the other hand, the Reynold's number was calculated using the physicochemical concentrate properties, i.e., using the density (ρ) and viscosity (μ) for the milk concentrate flowing inside the module.

In the results of the experiments was noticed that the membrane of 3.6 mm of d_h at the same Reynold's number, i.e., same turbulence state, shows a better behavior of limit flux than the 6 mm of d_h. This can be caused by the fact that smaller channels increase the substances back transport towards the bulk solution, reducing the solids concentration onto the membrane surface and, therefore, reducing the polarization concentration, increasing the flux (Cheryan, 1998).

The Table shows correlation equation and determination coefficient for each membrane. All experiences were carried out under turbulent flow.

Table: Correlations between Limit flux and Reynolds number for skim milk microfiltration

Membrane	Correlation
3.6 mm	$J_L=(3 \cdot 10^{-8} \cdot Re+0.0027) \cdot Re$

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d_h	
6 mm d_h	$J_L=(9\cdot10^{-8}\cdot Re+0.0024)\cdot Re$

For both hydraulic diameter membranes the determination coefficient (R^2) was higher than 94.41% . Both models were properly validated using the Komogorov-Sminov test, being accepted the hypothesis than the residuals come from a normal distribution with a 95% confidence (p-value>0.05).

In literature, few researches that relate limit flux and Reynold's number. For example, Baruah *et al.* (2003) found a linear relationship between J_L and Re, but they did not report the correlation equation between them. The correlations submitted by Samuelsson *et al.,* (1997a, 1997b) show a linear relationship between Re and J_L. While, Krstić *et al.*'s work (2002) show several expressions where J is proportional to Re up to c ($J \alpha Re^c$), where c<1 for all membranes analyzed with or without turbulence promoters. But, Krstić *et al.,* (2002) did not report the limit flux, they report only permeate flux measured under constant transmembrane pressure. However, by flux versus transmembrane pressure curve inspection, it can be noticed that the transmembrane pressure used by them would be in a zone where the limit flux was already achieved, for that reason; it was possible to compare results with the present work.

In all the above mentioned papers the concentration factor was not taken into account, for example, the Krstić *et al.'*s work (2002) was carried out using a full recirculation mode, i.e., only a concentration factor of 1.0 was used. In other paper, Krstić *et al.,* (2004) used different concentration factors (1 to 2). Hovewer, they did not report the flux behavior in relation to Reynold's number.

A nonlinear empiric relationship between limit flux and Reynold's number was found in this research. This can be a consequence of the analyzed variables ranges, being the most important, the concentration factor range used. This is contrary to the reported researches in literature. The concentration factor effect could be able to generate a curvature in the relationship between J_L and Reynold's number.

In conclusion, a validated correlation for limit flux and Reynolds number was obtained in this work. A equation type $J_L=aRe+bRe^2$ is accurate for describing the skim milk microfiltration under several experimental conditions.

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